Simulation of Air flow, Smoke Dispersion and Evacuation of the Monument Metro Station based on Subway Climatology

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This research is creating a working laboratory in Newcastle Monument metro station to understand the details of how the over ground climate influences the internal airflow and the impact this has on evacuation strategies. It is intended to link weather data with the background air flow in the station and identify the main driving forces for the dispersion of smoke or toxic agents throughout the station. The subway air flow will be evaluated and then interfaced with a VR simulation of the station and adjoining tunnels to produce a visual diagnostic and predictive tool. This data, with existing pedestrian movement modelling, will assist in identifying the correct evacuation procedures to minimise the exposure time of individuals to a smoke filled environment. The final outcome of this work will be a decision making process with regard to the initiation of effective measures to minimize the impact of fire within a subway that can be used at the initial design period to evaluate proposed evacuation routes.

Keywords: *Subway Climatology, Smoke and Fire CFD Simulation, Tunnel Safety, Emergency Ventilation*

INTRODUCTION

The first urban railway system and the world's first underground line (Metropolitan) opened on 10th January, 1883, in London to cope with population growth and increasing traffic congestion. Underground railway systems have become one of the important facilities of urban transportation however there is tremendous potential danger once a fire occurs in a subway system or a tunnel. These types of fires have some distinctive characteristics such as complicated burning process, rapid spread and high temperatures that disperse smoke very quickly. This creates problems in narrow and enclosed underground station passages (Yang et al., 2006) making evacuation difficult. Research shows that over 60% of all deaths in subway fires are attributable to people being either wholly or partially overcome by gas or smoke (Levy, 2010). The exposure time of individuals in a smoke environment depends upon their speed of movement and the direction they choose to travel. National statistics imply that the provision and correct location of emergency exit signs is of paramount importance (Chen, Chien, et al., 2003) as is providing effective smoke control systems and providing correctly located emergency exits and escape routes. The related research of verification of the effectiveness of smoke control system have been done by Tan (Tan et al., 2012). The research did at a typical subway station of Taipei propose an innovative smoke control scheme with a platform edge door (PED), which turns out to be much more efficient in evacuating smoke than that currently used (Chen, Guo, et al., 2003). This however requires an understanding of the air flow that is driving the motion and dispersion of the smoke. The aim of this research is to develop an understanding of the air flow in the Monument Metro Station in Newcastle upon Tyne and to link this with the movement of smoke or other agents. Producing a simulation of the dispersion of smoke and evacuation of passengers in a virtual reality (VR) environment will inform the decision making process in the event of a fire or emergency to assist in evacuation strategy. The VR data obtained from this study will extend the existing Virtual NewcastleGateshead data base (Morton et al., 2012).

This program of work includes laser scanning of the Monument Metro Station to capture an accurate model of the station from point cloud data which is then used as a background to display the air movement determined by using CFD models. The air flow will be evaluated and then interfaced with the VR simulation to produce a visual diagnostic and predictive tool that will display the background air flow within the station. This information can then be combined with pedestrian movement simulation created in the Legion software to determine the likelihood of pedestrians being overcome by smoke and to determine the most effective escape and evacuation strategy for a particular incident.

This research is timely because several existing subway systems in Europe have reached the age which need to be refurbished. There is also a need in some countries for the construction of new subways and tunnels. This research will strengthen decision making processes; improve the effectiveness of simulation in producing a safer environment in underground stations. This research methodology will also be applicable to many different types of large building and structures such as shopping centres, airports even large ships as the air movement is intimately linked to climatic conditions, ventilation systems, and local energy release from machinery such as electric motors

Justification of Monument Station for Research

The Monument Metro Station is the principal station on the underground section of the Tyne and Wear Metro system and is used by almost 6 million passengers per year (NEXUS, 2013). The total length of the underground section is 4 km encompassing 6 stations as shown in figure 1. The underground section of the north-south line goes from Jesmond station to Central Station and the east-west line has openings at Manors and St James. The two lines cross at the Monument station which is situated fully underground with the highest level being the ticket lobby area. It has four platforms on two tracks that cross at different levels. The platforms are accessed by escalators or lifts from the ticket hall and there are connecting stair wells between the different platform levels. The pedestrian entrances/exits to the station are in the Eldon Square shopping centre and at Grey Street and Blackett Street. This station is widely used by commuters travelling to the city centre.

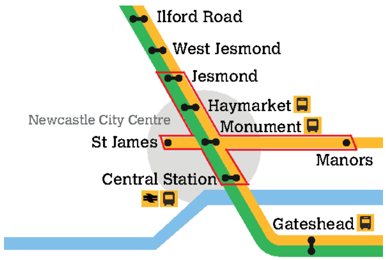


Figure 1
Underground Stations of the Tyne and Wear Metro System (NEXUS, 2013)

SUBWAY CLIMATOLOGY

From the early 70s, subway evacuation and tunnel safety in emergency situations in case of fire has aroused great concern (Apte et al., 1991; Policastro et al., 1998). The knowledge about airflow interdependencies with the outer atmosphere and investigated the effects of varying ventilation velocities of underground transport system is urgently needed. Subway Climatology as a new research field for the management of possible catastrophes in subway-systems which was proposed by Pflitsch and Küsel based on their work on cave systems. (Pflitsch et al., 2000; Pflitsch, 2001; Pflitsch et al., 2003). The aim of this present Subway Climatology research is to gain a better understanding of how air mixes between the subterranean levels and street-level (regional airflow) in a subway station and to identify the main driving forces for the dispersion of smoke or toxic agents throughout the station. It has been shown (Pflitsch et al., 2003) that a natural background air flow exists in a subway system that is active during the normal operation hours and influences the spreading of gases. This air flow is mainly driven by stack effect (Chen, Chien, et al., 2003) and independent of the train movements and re-establishes quickly after the passing of a train. The natural background air flow is driven by the over ground climate so it exhibits a seasonal variation similar to that found in the airflow of barometric caves. Understanding the influence of the background air flow on the ventilation of the subway system is important because it has a strong influence on the direction and strength of the internal air flow and air exchange within the station. This air exchange is strongly influenced by chimney effects within the underground buildings (for instance in escalator wells). A recent study (Pflitsch et al., 2013) has shown that, in the event of a disaster, airborne toxins in subway systems are dispersed mainly by air movements caused by natural ventilation and chimney effects that are produced by the pressure differential between station levels and street levels. Warm air within a station naturally flows upwards towards the over ground entrances by way of stairs and escalators. The addition of energy to the air from the escalator motors enhances the buoyancy effect accelerating and dispersion the air. However flow reversals or recirculation has been noticed between different levels in a station due to the interaction of the natural air flow with the station ventilation system (Pflitsch et al., 2012). This can lead to a blocking of normal exit routes making them unsafe and in the worst case making them death traps. As a consequence the influence of natural ventilation should be included in the disaster planning in order to develop effective strategies for the reaction to fires and the dispersal of smoke. Thus knowledge about the internal airflow and the interdependencies with the outer atmosphere is urgently needed.

Metro and subway system construction is on the increase world-wide with longer tunnels being built, often as parts of ever more complex transport systems. Every metro system is unique in terms of method of construction and layout of the stations (Beard, 2009). It is clear that the behaviour of a subway system should be considered together with the over ground climatology. The background air flow is very complex but recent advances in computing power and developments in programming have made it possible to approach an understanding of these flows using computational methods. Unfortunately the presentation of the air flow data is very difficult for non-experts (such as the metro operators) to understand so it is essential that a better means of displaying this information is also developed.

RESEARCH METHODOLOGY

The objectives of the project will be met by providing a platform that will promote shared understanding and transfer of knowledge and expertise and by furthering the development of Subway Climatology provide a safer environment for subway passengers. A working laboratory has been created at the Monument station by a consortium of Northumbria University, Ruhr University Bochum, Newcastle University and Nexus. Several parameters such as air flow velocity and direction, temperature and humidity data are being recorded and processed to reveal details of the sensitivity of the airflow momentum and energy transfer capacity on external factors such as the wind direction at the tunnel portals, the local over ground weather and internal factors. The work includes laser scanning of the station to produce a VR representation that will be used as a background for the display of air movement determined by using CFD but the VR files will also be used to generate a CFD model of the station. This will be combined with other models such as those to predict flow in stair wells (A. Zohrabian et al., 1989; A. S. Zohrabian et al., 1989). This will also be accompanied by tracer gas tests to validate the CFD results. The air flow data will then be used to determine the efficacy of evacuate routes, determine egress time and identify possible bottleneck locations in the station by combining the airflow results with an evacuation simulation using the propriety software LEGION. The eventual outcome will be an assessment of the evacuation scenario of the station that will inform designers and architects of the impact of building design features on the smoke dispersion and thus enhance security in the event of a fire in the subway.

Laser scanning and 3D modelling

A full laser scan of the Monument station, which contains 68 scans, has been produced. This includes the four platforms and tunnels, the concourse area, escalators and stairs and part of the surround building at the three exits as show in Figure 2 and 3. Figure 7 is a perspective view of Monument Metro station on the city centre map which shows the position of the underground structure.

The point cloud data has been converted manually to a 3D polygon mesh using the software 3ds Max. A point cloud plugin provides a simple solution to import point cloud data into 3ds Max called Clouds2Max. This is a very effective method that minimises the noise of the point cloud to produce smooth polygon models which can satisfy the accuracy required of CFD modelling. A simple model in 3ds Max of two tunnels and platforms located at the same level is shown in figure 4.

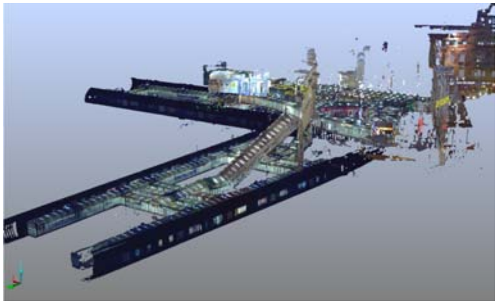


Figure 2
Point Cloud model of Monument Metro Station (1)

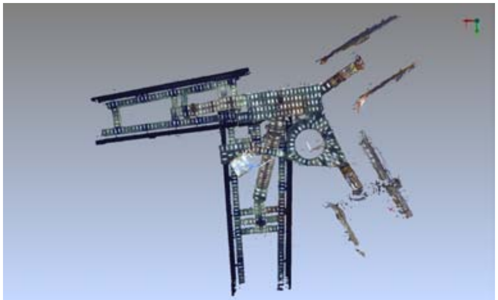


Figure 3
Point Cloud model of Monument Metro Station (2)

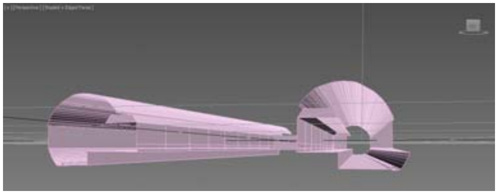


Figure 4
Model of two tunnels and platforms created in 3ds Max

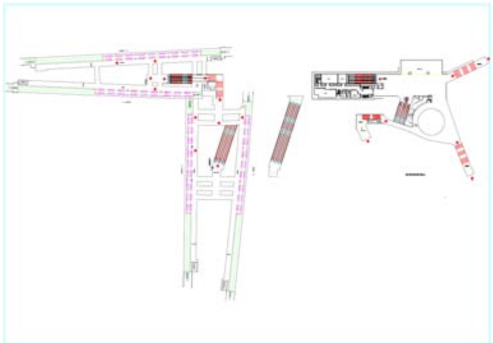


Figure 5
Location of the measuring points around Monument Metro Station

Figure 6
Ultrasonic anemometers installed in the tunnel

Figure 7
Location of the three measuring points at street level

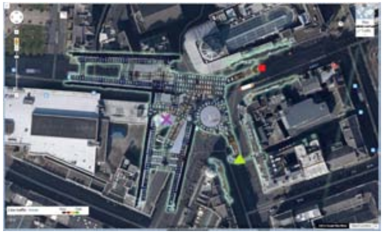


Figure 8
October Temperature Trend line (Logarithmic)

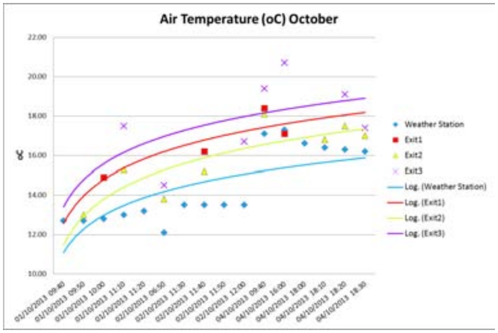
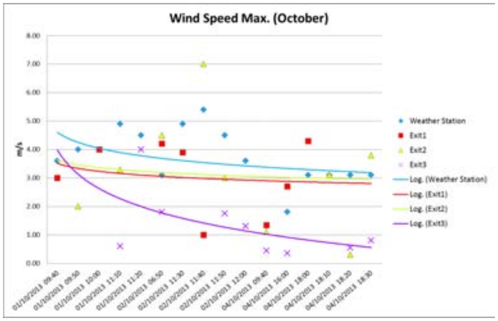


Figure 9
October Maximum Wind Speed Trend line (Logarithmic)



AIR FLOW MEASUREMENT AND WEATHER DATA ANALYSE

The measurement of temperature, humidity, wind speed and direction have been done at 20 points (as show in Figure 5) around the Monument Station including 3 points outside the exit at street level. These measurements have been taken 2 to 3 days every month from October 2013 and will be repeated until September 2014. This data will be used to validate the CFD modelling of air flow inside the station.

Ultrasonic anemometers have been used in relevant research (A Pflitsch et al., 2000) and installed inside the tunnel at Monument Station, Central station and Haymarket Station since 2009 as show in Figure 6. The measure data will used to define the boundary conditions in CFD modelling.

The three measurement points (as show in Figure 7) at the street level outside the three exits are intended to measure the micro climate of Newcastle City centre where the Monument station is located. Figures 8 and 9 show the results of comparing the temperature, minimum and maximum wind speed of the measured data with that recorded in a local weather station located at Northumbria University.

TRACER GAS EXPERIMENT

Different types of tracer gas experiments were complete in February 2014 by staff and students of Northumbria University and the Ruhr University Bochum. The tracer gas tests were carried out using Sulphur Hexafluoride (SF6), which is commonly used in dispersal analysis (Andreas Pflitsch et al., 2012). The special sensors for detecting the concentration of SF6 were designed and developed by the partners at Bochum, figure 10. A series of tests were performed including releasing the gas in a moving train and several tests were performed by releasing the gas at different locations in the station.

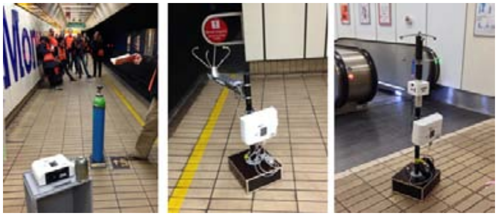


Figure 10
Release of SF6 at platform, SF6 sensors and ultrasonic anemometers

In experiment 4, the SF6 gas was released at the lower platform during an operational break. From previous research the natural background air flow had been identified as flowing from south to north in the then current weather condition. So it was expected that the SF6 would migrate northwards through the tunnel. A number of airflow sensors and SF6 sensors were placed throughout the station as shown in figure 11. Also shown is the SF6 release point indicated by the shape representing a gas bottle.

The concentration of the SF6 as it moved through the station is shown in figures 12, 13 and 14. The gas was released at 02:29:00, and within 2 minutes the sensors number 11, 13 and 14 detected very high concentrations of SF6 as shown in figure 12. The other sensors on this platform did not detect SF6 confirming the direction of the natural background air flow. Then a large amount of gas went to the upper platforms 3 and 4 through the connecting stair well as indicated by the red line (sensor 19) in figure 13. The tracer gas dispersed over the whole level of platforms 3 and 4 within 4 minutes and proceeded to flow down the tunnels and also up towards the concourse area through the escalator link as show in figure 13 (red line of sensor 1). The tracer gas sensors at the station exits, 5, 16 and 18 in the figure 14 indicated that most of the gas dispersed into Eldon square shopping centre (pale blue line sensor 16).

Other tracer gas experiment results also showed

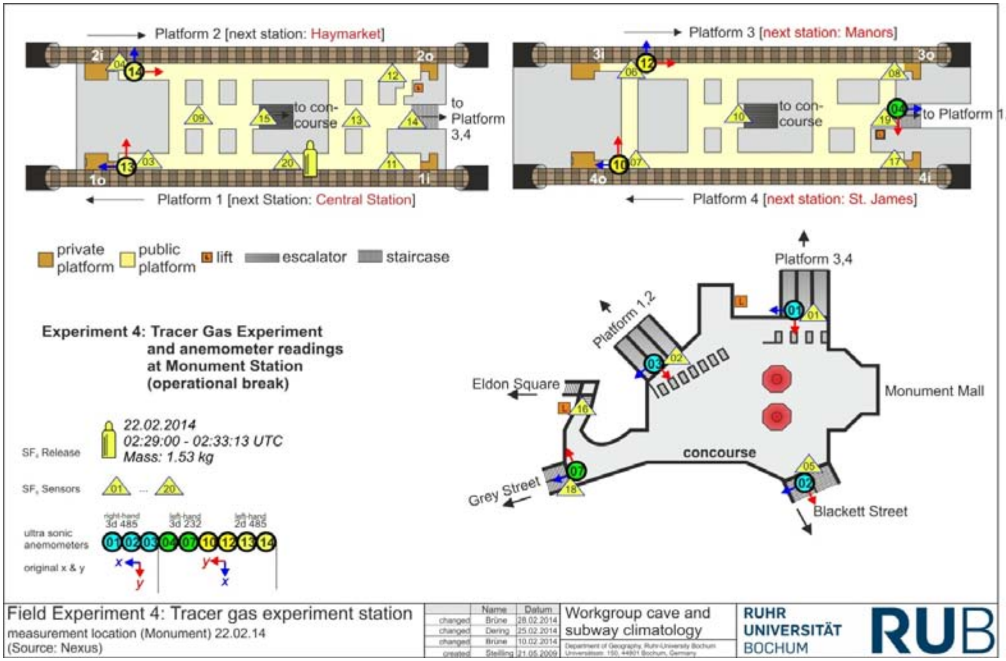


Figure 11
The location of anemometers, SF6 sensors and release point for test 4.

the dispersion of the gas throughout the whole stations under different conditions. The path of the tracer gas was most unexpected and this indicates the complexity of the flow regime that exists in stations making it difficult to predict the dispersion route of smoke and devise effective evacuation routes.

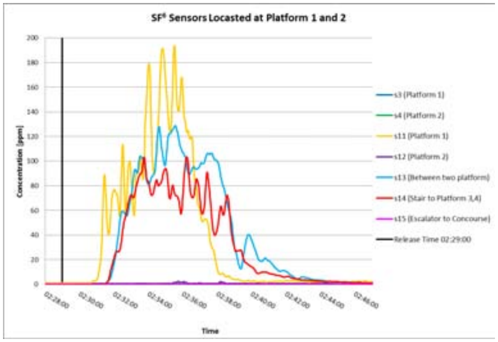


Figure 12
Concentration line diagram of SF6 sensors located at platform 1 and 2

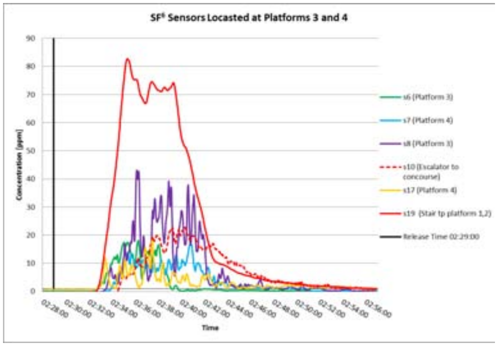


Figure 13
Concentration line diagram of SF6 sensors located at platform 3 and 4

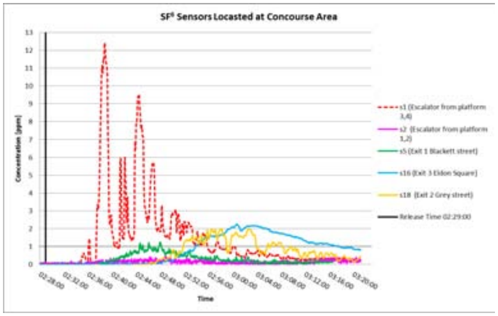


Figure 14
Concentration line diagram of SF6 sensors located at concourse area

PEDESTRIAN SIMULATIONS

The information obtained from the tracer gas experiments has been examined alongside the result of the evacuation simulation produced by the Legion software. As the research did at Alexanderplatz in Berlin which combining climate data from the tunnels, readings from tracer gas experiments and the results of the pedestrian evacuation, conclude into a better prognosis of safe and unsafe evacuation routes in certain situations (Brüne et al., 2014). The pedestrian simulation of Monument metro station considered the evacuation from 2 trains containing 250 people in each train at two different platforms at different levels. It was also considered that 50 people would be waiting on each platform and 50 people would be at the concourse area. The numbers of people evacuation with time is shown in Figure 15 and the evacuation route indicating the concentration of people is shown in figure 16.

It can be seen that the pedestrians are evacuate from 2 minutes to 7 minutes after the beginning of the evacuation. Overlaying the tracer gas results on this data provides an indication of the number of causalities that may be expected from an emergency incident. It can be seen that passengers on platform 1 south of the gas release point can safely exit the platform by way of the escalator to the concourse area. The tracer gas dispersed on the lower platforms (1 and 2) migrates through the stair well to platforms 3 and 4 (sensor 19) in around 4 minutes and then travels to the concourse area via the escalator in 7 minutes (sensor 1). This means that the passengers on platforms 3 and 4 and in the concourse area near these platforms are at greatest risk. The evacuation route from platforms 3 and 4 is less hazardous. It can be seen that there is some congestion on the stairs at the main exits to the concourse area but of great concern is the migration of the tracer gas dispersion to Eldon square shopping centre through exit 2 (sensor 16).

So for this situation the scenario of pedestrian evacuation will be: First, the passengers on platforms 3 and 4 should be evacuated as quickly as possible to the concourse area. The passengers on the lower platforms should leave the station by walking down the track southwards against the background air flow. This will take them away from the gas release site and reduce the congestion at the main exits to the station allowing speedier evacuation of the passengers on platforms 3 and 4.

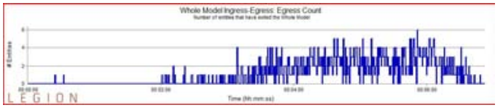


Figure 15
Numbers of people evacuation with time

Figure 16
Density of people at evacuation route

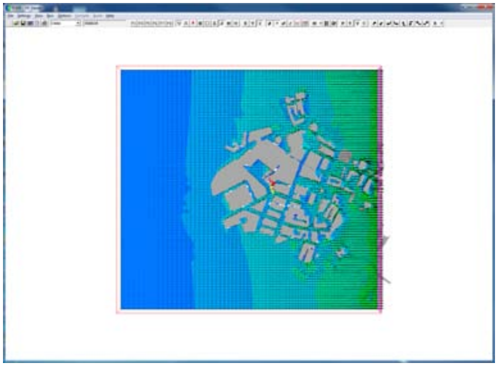


Figure 17
CFD simulation of Newcastle city centre micro climate

CFD SIMULATION APPLICATION IN TUNNEL AND SUBWAY STATIONS STUDIES

The tracer gas experiment combined with the pedestrian simulation gives a highly accurate results of evacuation plans but the tracer gas experiment only represents one weather condition so does not give a complete picture. In order to fully understand the air flow dynamics in the station it will be necessary extend this work to account for the seasonal variation of the weather. Previous research by Wilby (Wilby, 2005) shows that the local microclimate in cities is strongly influenced by the so called "heat island effect" in which the temperature and airflow are strongly influenced by the presence of buildings. This has been observed in Newcastle and reproduced by measurements and CFD simulation of the area around the Monument for a limited number of cases. The nearest weather station recording data on an hourly basis to the Monument station is on the university site approximately one half kilometres to the east and on the top of a 5 story building. The tests performed and shown in figures 8 and 9 show there is a loose correlation between the local weather data at the station and that recorded by the weather station. This is not accurate enough to be a reliable estimate of the situation at the monument but the weather station data can be used as an input to a CFD model of the area around the station. A whole year weather data can be simulating through this model as methodology to predict accurate climate outside station base on weather station data. Then use this micro climate data as an input of boundary condition in metro station CFD modelling. This has been done and is shown in figure 17 which shows the CFD model developed from the Virtual Newcastle Gateshead City Model.

In the fullness of time it is hoped to produce a comprehensive CFD model of the entire Monument station taking into account the variable local climate conditions, different operation situations and different fire locations. Relative researches (Simcox, et al., 1992; Chen, et al., 2003; Wen et al., 2007; Xiaojun, 2008; Gousseau, et al., 2011) of analyses and simulation ventilation, temperature distribution, smoke dispersion and smoke control carried out using CFD simulation in a tunnel or subway station. Numerical (CFD) three-dimensional simulations are providing the advantages such as accuracy, convenience, and cost-saving and provides the results in a format that can easily be post-processed to create animation.

CONCLUSION

The program of work outlined in this paper is intended to develop a methodology and a tool capable of analysing the airflow in subway systems that would include a CFD study of fire simulation and smoke movement and dispersion in a subway system. This research brings together complementary groups working in the fields of Subway Climatology, Virtual Reality, Pedestrian Simulation, Human Factors and Emergency Preparedness for gaining a better insight of the impact of a fire in a subway system. This research integrates domains of knowledge that hitherto have been used in isolation and in so doing brings a holistic approach that strengthens the decision making processes and improves the effectiveness of simulation and design exercises and will produce a safer environment for the travelling public.

The final outcome of this research can be assisting in operational planning for a possible incident for the Emergency Services, can be used as a training tool to familiarize maintenance workers with details of the tunnels for the subway operator and can also be used to simulate emergency incidents. It will be possible to assess escape and evacuation strategy for a particular incident. For the architects, designers and planners it will be used as an early stage design tool to assess the functionality of proposed new tunnels and station designs and examine the result of proposed changes in the layout of existing stations. This research methodology can be extended to many other types of buildings or structures such as airports, and shopping centres that are susceptible to the same risks as subway systems.

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